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Brain EM Exposure for Voice Calls of Mobile Phones in Wireless Communication Environment of Seoul, Korea

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ABSTRACT The aim of this paper is to present the measurement results of the transmitted (Tx) power levels of mobile phones in currently operating wireless communication networks in Seoul in 2015 and 2017 and the calculation results of the specific absorption rate (SAR) in the brain for voice calls while holding a mobile phone against the user's ear when operating at the measured mean power level. The Tx power levels of mobile phones using Code Division Multiple Access (CDMA) 2000, Wide CDMA (WCDMA), and Long-Term Evolution (LTE) networks were compared for the three main mobile network operators in South Korea. The actual mean Tx power level was less than 0.5% of the maximum power for the CDMA2000 and WCDMA networks. In the LTE networks, however, an extremely wide gap in Tx power was observed between the operators; two of the operators showed a mean power of less than 0.1% of the maximum, whereas the other showed mean powers of the three bands within the range of 0.8%–20% of the maximum power. The measurement results suggest that the SAR in the user's brain is strongly dependent on the year the phone was used, the user-subscribed mobile operator, and the proportion of time connected to the network/technology. The maximum 1-g peak spatial-average SAR (psSAR) level at the mean Tx power in an LTE network was 4.8 mW/kg (for a child head model). A maximum gap of 25 dB in the psSAR was observed between all networks considered.

INDEX TERMS Transmitted power of mobile phone, real environment, brain SAR, CDMA, WCDMA, LTE.

I. INTRODUCTION

Many studies on the health effects of electromagnetic field (EMF) radiation from mobile phones have focused on brain diseases, including tumors, attention deficit hyperactivity disorder (ADHD), and other cognitive behavioral problems [1]–[5]. Such focus is due to the fundamental use of mobile phones, which remains voice calls while held against the user's ear, despite the increasing diversification of mobile phone functions. In addition, the position of the phone when held against the ear produces a much higher specific absorption rate (SAR) in the brain compared to other positions for texting and accessing the Internet.

Technologies used in wireless communication systems are rapidly changing, and Code Division Multiple Access (CDMA), Wideband CDMA (WCDMA), and Long Term Evolution (LTE) networks are currently operated by the three mobile operators in South Korea. As shown in Table 1, CDMA and WCDMA services were launched in Korea during the late 1990s and the mid-2000s, respectively. CDMA networks have operated within the frequency bands of 824–849 MHz (CDMA2000 Band Class 0) and 1,750–1,780 MHz (CDMA2000 Band Class 4). WCDMA networks have operated within the frequency bands of 1,920–1,980 MHz (UMTS Band 1) (UL). Thus far, LTE service has been commercialized in Korea using only frequency division duplex (FDD). The LTE-FDD service launched in 2011 mostly included serviced data communication such as text message use and Internet access, and Voice over LTE (VoLTE) is now commonly used.

The evolution of wireless communication technologies has resulted in varying applications of user equipment (UE), including voice calls in close proximity to the ear, voice

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calls using earphones or hands-free kit, voice calls in speaker mode, and texting and Internet access when held away from the user's ear. The application generating the highest levels of electromagnetic (EM) absorption in the human organs, particularly the brain, is voice calls when the UE is held next to the ear. Factors affecting the brain SAR when making a voice call while holding the phone to the ear may include the operating frequency, antenna location, output power of the phone, the distance and direction of the user and phone from the connected base station, and the surrounding environment.

TABLE 1. Mobile communication technology change in Korea.

Tech. / Operator	CDMA Start	CDMA2000 Start	CDMA2000 end	WCDMA Start	LTE Start
O_A	1996.1 BC0[1]	2002.1 BC0		2007.3 B1[3]	2011.7 B1,3,5,7[4]
O_B	1997.10 BC4[2]	2002.5 BC4	2012.1	2007.3 B1	2012.1 B1,3,8
O_C	1997.10 BC4	2004.12 BC4		-	2011.7 B1,5,7

[1] CDMA Band Class 0 uplink (UL): 815–849 MHz
[2] CDMA Band Class 4 UL: 1,750–1,780 MHz
[3] UMTS Band1 UL: 1,920–1,980 MHz
[4] LTE Band 1 UL: 1,920–1,980 MHz
3 UL: 1,710–1,785 MHz
5 UL: 824–849 MHz
7 UL: 2,500–2,570 MHz
8 UL: 880–915 MHz

Numerous studies have been published on EM absorption in the human head or brain when exposed to radio frequency (RF) EMF radiation from mobile phones; however, most have focused on a constant transmitted (Tx) phone power, e.g., 1 W, and not the real Tx power. Although international standards have recommended a procedure to measure the peak spatial-average SAR (psSAR) for mobile phones used in close proximity to the ear [6], [7], such standards provide the psSAR at the maximum available Tx power of the phone in a controlled laboratory for compliance tests based on the safety limits specified in [8]–[10]. However, the Tx power of a mobile phone in an operating network is typically much lower than the maximum and is also time varying owing to the many factors mentioned above. Despite such a low power level in a real environment, public concerns regarding the possible health effects of electromagnetic (EM) radiation from mobile phones continue because such phone use is still spreading and evolving in terms of frequency and technology. Moreover, large-scale epidemiological studies have been conducted regarding the association between mobile phone use and diseases, particularly the risk of tumors [1], [2].

The purpose of this paper is to quantify the EM absorption in the human brain during voice calls when using mobile phones connected to operating networks in Seoul, one of the world's most densely populated cities. Power measurements of mobile phones in real environments were also carried out in all currently available CDMA2000, WCDMA, and LTE networks in Seoul in 2015 and 2017 under a long-term study. In this paper, the measurement method and results obtained are described. In addition, the brain SARs of children and adults from voice calls under exposure to the average Tx power are estimated.

TABLE 2. DUTs used for Tx power measurements.

Technology	Operator	Commercial Phone model[1]
CDMA2000	O_A	SM-B510SL
	O_C	SM-B510LL
WCDMA	O_A	SM-G906S
		LG-F400S
	O_B	SM-G906K
VoLTE	O_A	SM-G906S
	O_B	SM-G906K
	O_C	SM-G906L

[1] The same mobile phones were used for the measurements in both 2015 and 2017.

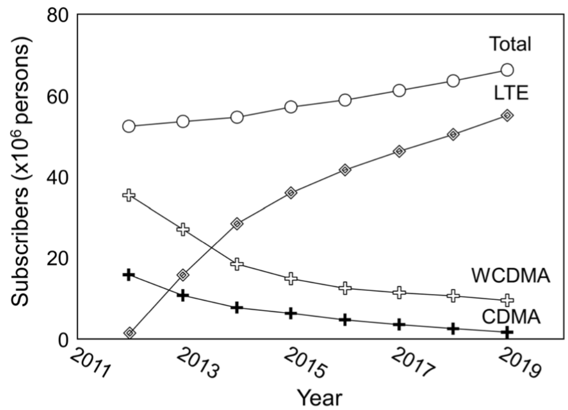


FIGURE 1. The subscribers of mobile communication services of Korea. The data were obtained from reports by the Ministry of Science, ICT and Future Planning, Korea. https://www.msit.go.kr/web/msipContents/contents.do?mId=OTg3.

II. MEASUREMENT METHOD

Korea has shown an extremely high growth in smartphone and LTE penetration in recent years. Fig. 1 shows changes in mobile subscriptions for CDMA, WCDMA, and LTE based on year. Although CDMA and WCDMA subscriptions are decreasing, LTE subscriptions are rapidly increasing. There are three major mobile operators in Korea (see Table 1). Operator O_A currently provides CDMA2000, WCDMA, and LTE networks, whereas operators O_B and O_C do not provide CDMA2000 and WCDMA networks, respectively.

A set of transmitted and received powers, (Tx, Rx) of eight phone devices under test (DUTs), shown in Table 2, were measured in Seoul for approximately a three-month period during the second half of both 2015 and 2017. Two DUTs (SM-G906S and LG-F400S) were employed to see the deviation in Tx power between different phone models under the same operator network. SM-B510SL and SM-B510LL operating using CDMA2000 networks are flip-type devices, and the remaining six models are bar-type phones. Because the Rx power is received through the DUT-linked channel, it differs from a real exposure incurred from all channels of the corresponding base station. In this study, the analysis is therefore focused on the Tx power from a phone, which is generally much higher than the Rx power.

Seoul has a population density of approximately 16,500 persons/km^2 with a total of 25 administrative districts. Each district is further divided into approximately 10 to 25 neighborhood units. The global positioning system (GPS) data and time information are also recorded along with the Tx power for each DUT in voice call mode. To derive the representative power distribution in Seoul, it was necessary to conduct even measurements across Seoul within the planned period. Therefore, a vehicle-based measurement method was chosen; the power data were mostly collected while driving along side streets in densely populated residential and commercial areas for longer than approximately 40 min in each neighborhood. Side streets have no demarcation between driveways and sidewalks and their widths are usually less than 9 m. Raw data recorded by the measurement system were averaged and stored every 1 s.

On the side streets, the maximum traffic speeds are restricted to 30 km/h. The quality of the communication signal is maintained by controlling the UL power. Owing to the multipath fading profile, the quality will be dependent on the moving speed of the mobile phone. A mobile device moving at a faster speed will have a more fading impact, and require more power resources.

In 2015, LTE DUTs were locked to their corresponding networks, and the use ratios of LTE bands were analyzed for each operator. However, they were unlocked in 2017 to determine what proportion of time O_A and O_B were connected to WCDMA and LTE networks for voice calls in a real environment.

FIGURE 2. **DUTs examined in a vehicle.**

Fig. 2 shows the configuration of the DUTs placed in a vehicle. The DUTs were connected to equipment (OPTis-P8E, Innowireless Co., Ltd.) and controlled by software installed on a notebook computer. The software logs the information on the time, GPS, Tx power, Rx power, and other factors provided by the chipset of the mobile phone. All DUTs of Table 2 were fixed at the same position using a transparent acrylic apparatus with low dielectric properties near the windscreen, as shown in the figure. However, because the phones placed at this position did not touch the human head, the Tx power needed to be compared with that of a phone operated while held against the ear. Therefore, as a preliminary measurement, two mobile phones of the same model, SHW-M460D, were operated and compared for the WCDMA network of operator O_A. The measurement data were gathered for approximately 10 h with one phone placed near the windscreen of the vehicle and the other held against the ear of a specific anthropomorphic mannequin (SAM) phantom, which is the standard head model used for an SAR test of a mobile phone (see Fig. 3).

FIGURE 3. **A DUT against SAM phantom in a vehicle.**

As described in Section III, the measured data were statistically analyzed for the mobile communication networks used by each operator.

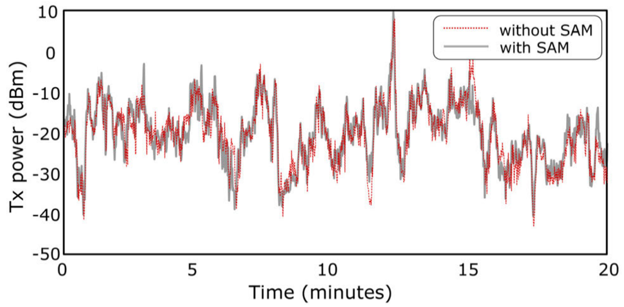
III. MEASUREMENT RESULTS

A. GENERAL

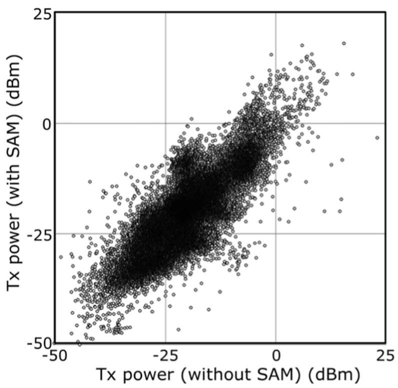
The measurements were conducted mostly between 10:00 and 20:00 on weekdays for approximately three months in 403 out of the total 423 neighborhoods in Seoul, which is a coverage of more than 95%. The number of data samples averaged over 1 s and logged at 1-s intervals was more than 1×10^6 (approximately 278 h) per DUT. The samples were sufficient to estimate the statistical uplink (UL) exposure of the Seoul population from mobile phone radiation during voice calls.

As mentioned earlier, although the maximum vehicle speed on the side streets is 30 km/h, the average vehicle speed during the measurement in real situations was much lower owing to the presence of traffic signs and child protection zones.

The effect of the SAM phantom on the Tx power of each phone was investigated for a WCDMA network (see Fig. 4). Figs. 4 (a) and (b) show line graphs for a segment of time and a scatter plot of all data samples taken during an approximately 10-h timeframe, with one phone placed near the windscreen of the vehicle and the other held against the ear of the SAM phantom. If the RF performance of the two phones is the same, the phone mounted on the SAM phantom may radiate slightly higher power owing to the hand phantom attached



(a) Data comparison in time domain



(b) scatter plot (10 hours)

FIGURE 4. **Comparison of Tx power with and without SAM phantom (WCDMA network) (without SAM, mean = 0.075 mW, SD = 1.24; with SAM, mean = 0.086 mW, SD = 0.84).**

near the antenna. However, a significant difference in Tx power was not shown, and thus the Tx power measured in the position without a SAM phantom, as shown in Fig. 2, was applied to the SAR estimation of the human brain, as described in Section IV.

B. CDMA2000 AND WCDMA NETWORKS

The occurrence frequencies at the logarithmic scale (dBm) of the Tx power of each operator network were extremely close to a normal distribution. It is well known that shadowing or slow fading in a land-mobile channel is usually described as a stochastic process having a log-normal distributed amplitude [11]. The average vehicle speed during the measurement was slow (approximately 10 km/h) owing to the presence of traffic signs and child protection zones. Furthermore, because the number of power samples measured in this study was extreme large ($>1 \times 10^6$), it seems that the histogram for the Tx power in the logarithmic scale was close to the normal distribution according to the central limit theorem. Fig. 5 shows the probability distributions (with 1-dB intervals) of the power samples measured for the WCDMA network of operator O_A in 2015 and 2017. It can be seen that the average power level was reduced in 2017 in comparison to that of 2015.

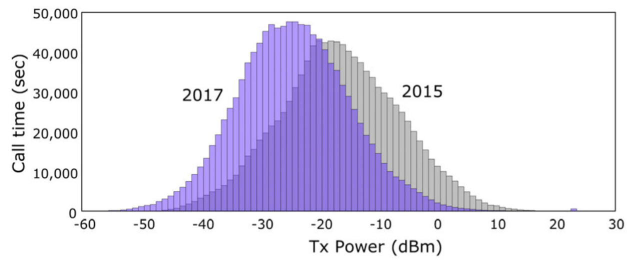


FIGURE 5. **Histograms for Tx power (operator O_A in WCDMA network).**

For the CDMA2000 and WCDMA networks, the cumulative distributions of the Tx power samples are shown in Fig. 6. The results of two DUTs (SM-G906S and LG-F400S) connecting to the WCDMA network of O_A are also shown; good agreement is demonstrated during 2015 (Fig. 6 (a)), but a gap (approximately 2 dB) can be observed for 2017 (Fig. 6 (b)). The type of vehicle, the apparatus used for fixing the DUTs, and the DUT location in the vehicle were also all the same in both 2015 and 2017. Therefore, a change in the performance of the semiconductor components of the DUTs, during the two years between observation periods might be the cause of this difference; however, the gap between the mean values was insignificant (see Table 3).

As observed in Fig. 6, the power levels in the WCDMA networks were lower than those in the CDMA2000 networks for both years, and the power levels of both decreased in 2017 compared to 2015. As shown in Figure 1, CDMA2000 and WCDMA subscribers have decreased each year, and according to the statistics of the Ministry of Science and ICT of Korea, the total data traffic of WCDMA has decreased significantly from 5659 TB in 2015 to 1520 TB in 2017. This seems to have resulted in a decrease in Tx power of mobile phones in 2017 as compared to 2015.

For each network, the two types of mean Tx power were calculated 1) by averaging the power samples in decibel milliwatts and then converting the power into milliwatts and 2) by converting each power sample in decibel milliwatts into the corresponding sample in milliwatts, and then calculating the arithmetic mean; hereafter, the former and latter averages are referred to as mean (log) and mean (linear), respectively.

A large mobile phone output survey using software-modified GSM phones was published in Europe in 2009 [13]; measurements of over 60,000 phone calls showed that the average Tx power was approximately 50% of the maximum, and the maximum power was used during a considerable proportion of the call time. However, in WCDMA networks of Europe, much lower average output power levels, compared with 2G GSM networks, were reported in a network-based measurement study in Sweden [14] and a drive-test study in France [12]. Both studies showed that the mean Tx power in outdoor environments was less than 1% of the maximum power.

The statistical results are shown in Table 3. The mean (log) for each DUT is almost the same as the median (the 50th

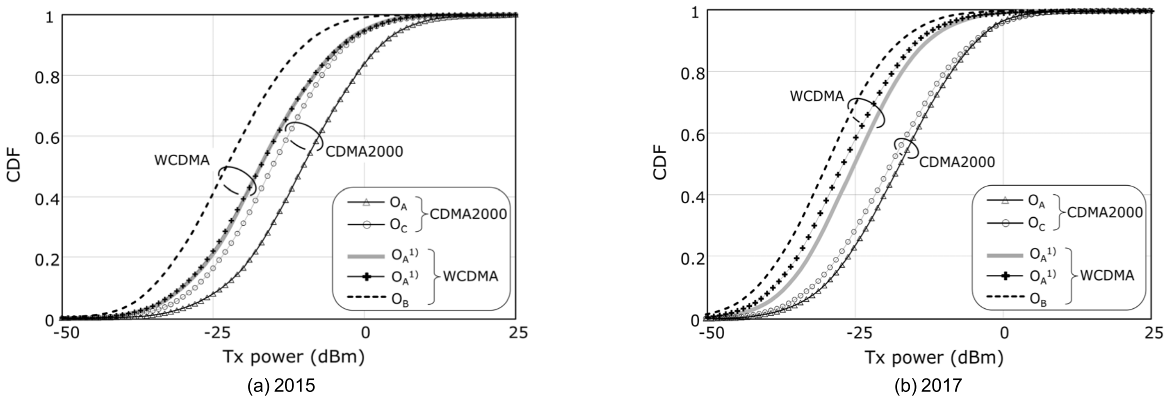


FIGURE 6. CDF for Tx power samples of mobile phones. 1)Two different DUTs were used for comparison: —— SM-G906S, —+— LG-F400S.

TABLE 3. Tx power in CDMA2000 and WCDMA networks.

(a) 2015

Technology	Operator	DUT (phone model)	UL frequency band	Tx power (mW)[1)]				
				10^{th}	50^{th}	90^{th}	Mean (log)	**Mean (linear)**
CDMA2000	O_A	SM-B510SL	824–829	5.0×10^{-3}	1.1×10^{-1}	2.051	1.11×10^{-1}	**1.239**
	O_C	SM-B510LL	1,770–1,780	1.8×10^{-3}	3.4×10^{-2}	5.64×10^{-1}	3.33×10^{-2}	**6.65×10^{-1}**
WCDMA	O_A	SM-G906S	1,950–1,960	1.1×10^{-3}	2.1×10^{-2}	4.67×10^{-1}	2.25×10^{-2}	**4.33×10^{-1}**
		LG-F400S		1.1×10^{-3}	2.2×10^{-2}	4.84×10^{-1}	2.23×10^{-2}	**3.87×10^{-1}**
	O_B	SM-G906K	1,970–1,980	3.5×10^{-4}	5.9×10^{-3}	1.13×10^{-1}	6.10×10^{-3}	**9.61×10^{-2}**

[1)] Total call time (or the number of power samples) for each network was approximately 1.05×10^6 s.

(b) 2017

Technology	Operator	DUT (phone model)	UL frequency band	Tx power (mW)[1)]				
				10^{th}	50^{th}	90^{th}	Mean (log)	**Mean (linear)**
CDMA2000	O_A	SM-B510SL	824–829	1.0×10^{-3}	2.1×10^{-2}	4.21×10^{-1}	2.07×10^{-2}	**3.57×10^{-1}**
	O_C	SM-B510LL	1,770–1,780	6.7×10^{-4}	1.5×10^{-2}	3.86×10^{-1}	1.55×10^{-2}	**3.26×10^{-1}**
WCDMA	O_A	SM-G906S	1,950–1,960	2.5×10^{-4}	3.6×10^{-3}	6.19×10^{-2}	3.82×10^{-3}	**2.15×10^{-1}**
		LG-F400S		1.4×10^{-4}	2.1×10^{-3}	3.77×10^{-2}	2.30×10^{-3}	**2.20×10^{-1}**
	O_B	SM-G906K	1,970–1,980	8.0×10^{-5}	1.3×10^{-3}	2.13×10^{-2}	1.29×10^{-3}	**3.10×10^{-2}**

[1)] Total call time (or the number of power samples) for each network was within the range of approximately 1.12×10^6 to 1.13×10^6 s.

percentile) because a probability distribution of the Tx power samples is close to normal. It can be seen that the mean (linear) is approximately 10–20 dB higher than the mean (log).

As shown in Table 3, the Tx power levels in both the CDMA2000 and WCDMA networks are less than 1% of the maximum available power (approximately 250 mW) of the DUTs even for the 90^{th} percentile power values. In this study, the mean (linear) is applied to an exposure assessment in the human brain owing to mobile phone calls (see section IV). The 50^{th} percentile and mean (linear) results of the WCDMA networks in Table 3 have orders of magnitude comparable to those reported in [12] and [14].

C. LTE NETWORKS

Before the service launch of LTE, the technologies and frequency bands of mobile networks had already been determined for each given Korean phone model. However, although the user is exposed to radiation of only a single-frequency band of a particular phone at a specific time, since the emergence of the LTE system, mobile phones have been able to use multiple frequency bands allocated for LTE services.

The authors analyzed the frequency bands used by the three operators based on the measured results from the LTE networks. The frequency allocation to each operator for its mobile communication service can change each year through a spectrum auction. However, although a certain band is allocated to a specific operator, its availability in a real environment becomes another matter.

Table 4 shows the connection ratios between LTE bands for the VoLTE services of the three operators. In 2015, a measurement was conducted using DUTs locked to LTE networks, as described in Section II. Two bands per operator were

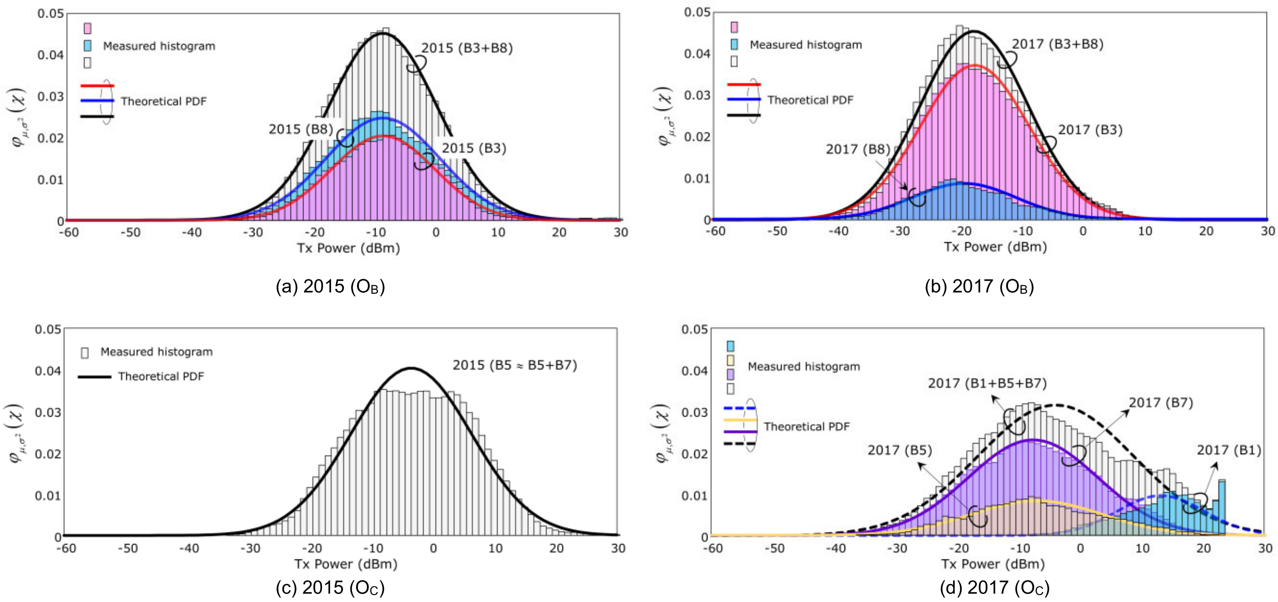


FIGURE 7. Histogram and PDF of Tx power for VoLTE.

observed, the use ratios of which differed; LTE B5 was mostly the only band used by Operator O_C, as shown in Table 4 (a).

In 2017, more frequency bands were allocated to the operators. It has been assumed that many users use their phones with the original factory settings. Therefore, SM-G906S (DUT of O_A) and SM-G906K (DUT of O_B) not locked to an LTE network, namely, with 'automatic' network mode selected, were employed for the measurements. These are the same phone models and the last letter of the model name indicates the initials of the operator. The default option for the call settings of SM-G906S and SM-G906K was "HD Voice off" and "HD Voice on," respectively, in automatic network mode. "HD Voice off" indicates that VoLTE service is blocked, and voice service is delivered through a WCDMA network. The Tx power of SM-G906S for O_A was logged in a WCDMA network during most of the total call time, as shown in Table 4 (b).

Many O_A subscribers would have made voice calls in a WCDMA network rather than in an LTE network in both years if they had not forced their phone to connect to only LTE networks. The DUTs of O_C did not need to be locked to an LTE network because O_C does not provide WCDMA service. Recently, the output power level distributions of LTE UE were determined using data applications based on an extremely large number of samples collected in an LTE network in Sweden [15]. The study was conducted through network-based measurements on approximately 7,000 UE, and a mean output power of less than 1% of the maximum was reported for all environments considered (rural, suburban, urban, and indoor).

Table 5 shows the 10^{th}, 50^{th}, and 90^{th} percentile and the mean values of the Tx power for each LTE network in Seoul. Extremely different levels were observed between the

TABLE 4. Service operators and observation of LTE band connection (%).

(a) 2015 (locked to LTE network)

Band (UL[1]) \ Operator	O_A	O_B	O_C
B1 (1.9 GHz)	*	*	0.0
B3 (1.7 GHz)	21.6	42.9	*
B5 (800 MHz)	78.4	*	99.3
B7 (2.5 GHz)	*	*	0.7
B8 (900 MHz)	*	57.1	*
Sum (%)	100.0	100.0	100.0
Total call time (s)	1.05×10^6	1.05×10^6	1.05×10^6

[1] UL frequency
* not allocated band.

(b) 2017 (unlocked to LTE network)

Band (UL) \ Operator	O_A	O_B	O_C
LTE B1 (1.9 GHz)	0.0[1]	0.0[1]	17.1
LTE B3 (1.7 GHz)	14.1	81.9	*
LTE B5 (800 MHz)	4.9	*	22.1
LTE B7 (2.5 GHz)	0.0[1]	*	60.8
LTE B8 (900 MHz)	*	18.1	*
LTE sum (%)	19.0	100.0	100.0
WCDMA (1.9 GHz)	81.0	0.0[1]	*
Total Sum (%)	100.0	100.0	100.0
Total call time (s)	1.12×10^6	1.11×10^6	1.13×10^6

[1] allocated but not available.
* not allocated band.

two years. In 2015, the mean (linear) of the three operators was lower than 2% the maximum, and the inter-operator difference of the mean (the highest/lowest mean) between the networks was five times, as shown in Table 5 (a). In 2017, the mean of O_A and O_B dropped to below 0.1% of the maximum in all networks. At the time, the number of installed

TABLE 5. Tx power in LTE networks.

(a) 2015 (locked to LTE network)

Technology	Operator	DUT	UL frequency band (MHz)	Tx power (mW)[2)]				
				10th	50th	90th	Mean (log)	**Mean (linear)**
VoLTE	O_A	SM-G906S	B3 (1,715–1,735)	5.2×10^{-3}	8.5×10^{-2}	1.227	8.32×10^{-2}	**9.93×10^{-1}**
			B5 (829–839)	9.0×10^{-3}	1.6×10^{-1}	2.576	1.64×10^{-1}	**2.889**
	O_B	SM-G906K	B3 (1,735–1,755)	1.2×10^{-2}	1.4×10^{-1}	1.656	1.41×10^{-1}	**1.293**
			B8 (905–915)	1.0×10^{-2}	1.3×10^{-1}	2.089	1.40×10^{-1}	**4.548**
	O_C	SM-G906L	B5 (839–849)	2.3×10^{-2}	4.5×10^{-1}	8.166	4.47×10^{-1}	**5.000**

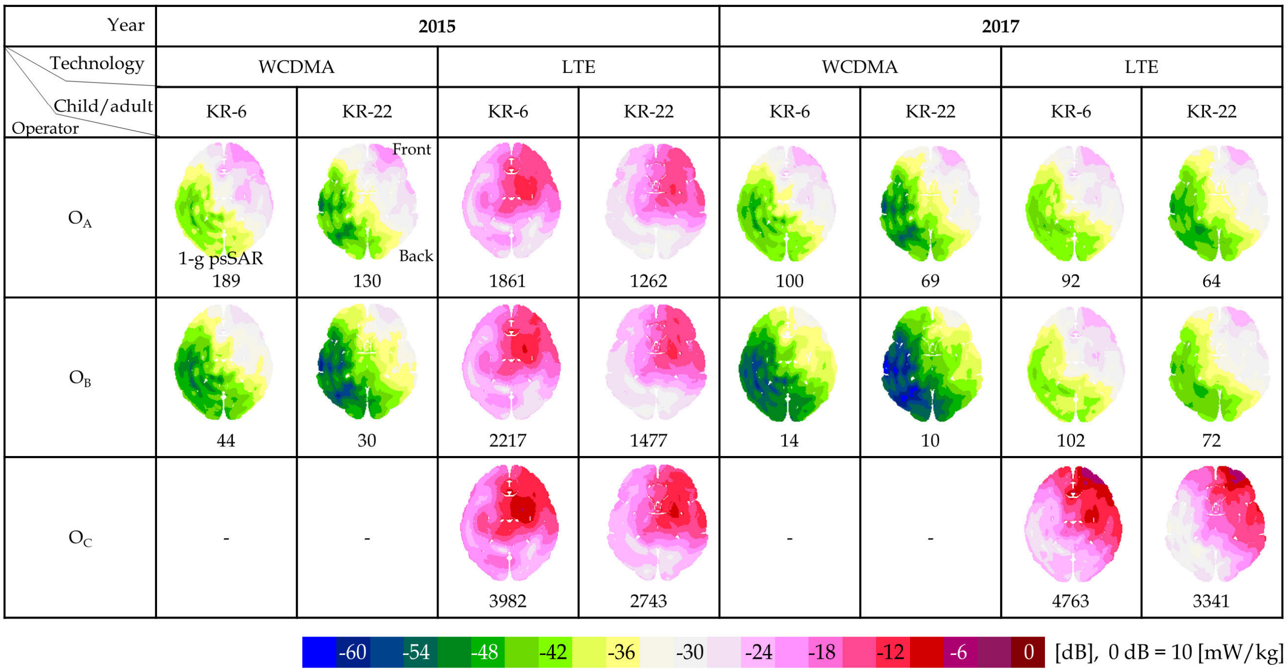
1) The total call time of each DUT was about 1.05×10^6 s. The connection ratios between bands are given in Table 4.

(b) 2017 (unlocked to LTE network)

Technology	Operator	DUT	UL frequency band (MHz)	Tx power (mW)[2)]				
				10th	50th	90th	Mean (log)	**Mean (linear)**
VoLTE	O_A	SM-G906S	B3 (1,715–1,735)	1.0×10^{-3}	1.3×10^{-2}	2.07×10^{-1}	1.31×10^{-2}	**9.75×10^{-2}**
			B5 (829–839)	1.8×10^{-3}	3.4×10^{-2}	5.57×10^{-1}	3.05×10^{-2}	**2.40×10^{-1}**
	O_B	SM-G906K	B3 (1,735–1,755)	1.5×10^{-3}	1.7×10^{-2}	2.67×10^{-1}	1.89×10^{-2}	**2.45×10^{-1}**
			B8 (905–915)	1.1×10^{-3}	1.0×10^{-2}	1.62×10^{-1}	1.19×10^{-2}	**1.38×10^{-1}**
	O_C	SM-G906L	B1 (1,920–1,940)	2.009	25.704	159.956	20.324	**50.542**
			B5 (839–849)	7.9×10^{-3}	1.7×10^{-1}	5.689	1.95×10^{-1}	**2.936**
			B7 (2,520–2,540)	7.3×10^{-3}	1.6×10^{-1}	4.477	1.69×10^{-1}	**1.932**

1) Total call time of each DUT was in the range of about 1.11×10^6 to 1.13×10^6 seconds (Table 4). The call time of SM-G906S in the LTE network of O_A is approximately 19% of the total call time. The connection ratios between bands are given in Table 4.

TABLE 6. Cross-sectional view of brain SAR and 1-g psSAR [μ W/kg] (at the mean power).



Year	2015				2017			
Technology	WCDMA		LTE		WCDMA		LTE	
Operator \ Child/adult	KR-6	KR-22	KR-6	KR-22	KR-6	KR-22	KR-6	KR-22
O_A	189	130	1861	1262	100	69	92	64
O_B	44	30	2217	1477	14	10	102	72
O_C	-	-	3982	2743	-	-	4763	3341

base stations for LTE was steadily increasing, and thus it is estimated that the Tx power of the mobile phones decreased. However, O_C additionally operated two new bands B1 and B7, and extremely high Tx power results of B1 can be seen in Table 5 (b), although the portion of call time for B1 is only 17% of the total (see Table 4).

Fig. 7 shows the histogram and corresponding theoretical probability density function (PDF) for the Tx power samples (in dBm) of O_B and O_C. Each PDF was obtained using the mean (log) (μ) and standard deviation (SD) (σ) of the histogram. Note that the histogram is expressed in density and not frequency. As in CDMA2000 and WCDMA networks, the Tx power probability distribution for each LTE network is also extremely close to normal. However, the histogram of B1 for O_C in Fig. 7 (d) is not normally distributed and seems to be due to an incomplete network construction for a newly introduced band. This indicates that Tx power of close to the maximum was transmitted for a considerable portion of the time.

The total call time of each DUT is longer than 10^6 s (see Table 5). The frequency band information is extremely important for the exposure estimation in the human brain because the electromagnetic penetration becomes deeper at a lower frequency. Based on the measurement results of the Tx power, the estimated SAR distribution in the human brain for the different technologies of each operator is described in the next section.

IV. ESTIMATION OF BRAIN SAR

The authors previously implemented representative head models of Korean males [16] and investigated age-related differences in the brain for radiation from mobile phones [17], for which three numerical bar phone models with a dual-band built-in antenna operating at 835 and 1,850 MHz were employed. Prior to the implementation of the human head models, the numerical phone models were developed from an analysis of the SAR test reports of more than 300 commercial bar phone models with an internal antenna at the bottom of the phone body, which is the most common type in Korea. The WCDMA and LTE phones listed in Table 2 correspond to this type. One of the numerical phone models is M_{avg} ($61 \times 120 \times 12$ mm^3) and has typical characteristics of a bar phone in terms of the dimensions, antenna location, SAR distribution in the flat phantom, and 1-g psSAR levels in the SAM phantom [18].

The main antenna of all DUTs used for the measurements is located at the bottom of the phone body. In this section, the SAR in the brain from voice calls using WCDMA and LTE networks is estimated based on the SAR simulation results of the average numerical bar phone model M_{avg} because the number of CDMA2000 subscribers in Korea has significantly decreased, as shown in Fig. 1. The SAR in the human brain under exposure to the average maximum available power of commercial phone models was previously reported [17], [19]; after calculating the SAR at the two standard phone positions against the head, the two SAR distributions of the head model were spatially averaged.

In [17], the brain SAR distributions of representative 6- and 22-year-old male head models (denoted as KR-6 and KR-22, respectively) for a numerical phone model M_{avg} operating at 835 and 1,850 MHz were reported. The distributions correspond to those at the average maximum power for commercial phone models.

The UL frequency bands of the WCDMA and LTE networks shown in Tables 3 and 5 were classified into two frequency groups: LTE B5 and LTE B8 for the low-frequency (LF) group, and WCDMA, LTE B1, LTE B3, and LTE B7 for the high-frequency (HF) group. Except for LTE B7, all UL frequencies showed a difference of within 10% from 835 to 1,850 MHz for the LF and HF groups, respectively. An LTE service for B7 was recently launched by O_C and there are no representative numerical phone models in this band yet owing to insufficient information on commercial phone models. Instead, in this study, the SAR distribution at 1,850 MHz was employed for LTE B7.

Equation (1) provides a 3D SAR distribution of the brain, SAR_{real} (x,y,z), for a voice call in a real network:

$$\mathrm{SAR}_{real}(x, y, z) = \sum_f \left\{ \mathrm{SAR}_{\max,f}(x, y, z) \cdot \frac{\mathrm{P}_{real,f}}{\mathrm{P}_{\max}} \cdot \frac{\mathrm{t}_f}{\mathrm{t}_{total}} \right\} \tag{1}$$

where $SAR_{real,f}$(x,y,z) is a brain SAR at a specific point (x, y, z) for the actual Tx power level of the network, and the subscript f indicates the corresponding frequency. The proportion of connections of the frequency band corresponding to f for the total call time is denoted as t_f/t_{total}. Table 4 shows the portion of time connected to each frequency band over the total measurement time in the networks. Here, $P_{real,f}$ and P_{max} indicate the actual Tx power in the environment and the maximum power, respectively. In addition, $SAR_{max,f}$ (x,y,z) indicates a brain SAR at the maximum Tx power, as given in a previous study [17], and as mentioned above.

Table 6 shows cross-sectional SAR views and the 1-g psSARs of the brain for KR-6 and KR-22, obtained using (1) at the mean (linear) Tx power levels measured for the WCDMA and LTE networks of the three operators. The cross-sectional view was obtained at the middle of the brain and all 1-g psSARs were found within the temporal lobe.

The 1-g psSAR values of the WCDMA networks are exactly proportional to the mean Tx power because the frequency bands of the two operators are similar (see Table 3). In the LTE networks of O_A and O_B, all Tx power levels decreased in 2017 by one order of magnitude. However, the situations of the two operators were extremely different.

In the case of O_A, the proportion of the connection of LTE B5 reached almost 80% in 2015 (locked to an LTE network) but the LTE phone for voice calls was connected to a WCDMA network in 2017 when it was unlocked from the LTE network. Therefore, the 1-g psSAR for 2017 is about 1/20th that for 2015 because the Tx power level of the 2015 LTE B5 is much higher than that of the 2017 WCDMA and because the SAR is higher in the brain at a lower frequency (LTE B5). If the users had not set their phone to an LTE-only connection even in 2015, the SAR of the LTE networks of O_A would have been similar to that of the WCDMA network.

In the case of O_B, the DUT was observed to connect to only LTE networks regardless of whether the LTE-only connection on the DUT was forced. The 1-g psSAR of 2017 is about 1/20th the level of 2015, similar to the case of O_A. This was caused by a combination of the connection ratios between B3 and B8, and their actual mean Tx power, shown in Tables 4 and 5, respectively.

More LTE bands were managed by O_C in 2017 but not all of the networks were stable; the resultant SAR showed a slight increase in 2017. In 2015, all operators mainly managed lower frequency bands such as LTE B5 and B8 to provide coverage over a larger area. Their use ratios at higher frequency bands such as LTE B1, B3, and B7 increased in 2017.

V. SUMMARY AND DISCUSSION

The Tx power level during the voice calls of mobile phones was investigated as the first stage of a long-term plan to monitor the exposure levels in the mobile communication environments of Seoul. It took approximately three to four months to collect the Tx power samples of eight mobile phones concurrently using software installed on a notebook computer. The measurements were conducted in Seoul every other year (2015, 2017, and 2019). The measurements for 2019 included a portion of the new 5G radio network, the analysis of which is still ongoing. In this study, the brain SAR caused by the mean Tx power in a real environment was also estimated based on the results from previous research [16]–[19] conducted in part as an exposure assessment under the Mobi-Kids Study. The main findings are summarized as follows.

A. Tx POWER LEVELS OF MOBILE PHONES

The Tx power levels in all networks in operation during 2015 decreased in 2017. The mean Tx power in the WCDMA and LTE networks for O_A and O_B was below 0.1% of the maximum in 2017. However, the newly introduced LTE B1 network of O_C showed an extremely high mean Tx power (20% of the maximum) and an unstable probability distribution. Consequently, a larger Tx power gap (maximum of 27 dB) for LTE than for CDMA2000 and WCDMA between the networks of the different operators occurred in 2017. These results suggest that the time-averaged EM absorption in the user's brain during the call time is heavily dependent on the time (year) of phone use and the user-subscribed mobile operator, as well as on the proportion of connection time of the networks/technologies.

B. BRAIN SAR FOR VOICE CALLS IN REAL ENVIRONMENTS

The most common type of mobile phone is currently a bar-type with an internal antenna at the bottom of the phone body. For WCDMA and LTE networks, the same type of DUTs were used for the measurements, and the brain SAR of the KR-6 and KR-22 head models was estimated at the mean Tx power level. The band-connection ratios between the frequency bands were applied to the SAR distributions at the corresponding frequency as the weighting factors in the LTE networks. As a result, the brain 1-g psSAR level in the WCDMA and LTE networks was a maximum of 4.8 mW/kg when averaged over 1 g (KR-6 in LTE networks of O_C), which corresponds to approximately 0.3% of the psSAR limits (1.6 W/kg over 1 g). The brain 1-g psSAR for the child head model, KR-6, was 40–50% higher than that of KR-22, and a maximum gap of 25 dB in the brain 1-g psSAR was observed for the mean powers of all networks of the three mobile operators considered (see Table 6).

VI. CONCLUSION

The final goal of this study was to quantify the cumulative electromagnetic exposure in the brain for voice calls using a mobile phone placed against the user's ear in a real environment. In this study, the Tx power levels of the mobile phones were measured in networks of different mobile operators in Seoul, and the SAR levels in the human brain at different ages were compared at the mean power level used by the WCDMA and LTE networks.

Mobile communication technologies are rapidly evolving, and public concern regarding the adverse health effects of electromagnetic exposure continues. The local maximum SAR in a user's brain is much lower than the current SAR limits, although this depends highly on the operator networks to which the user subscribes. Moreover, the measured Tx power of mobile phones showed large changes depending on the measurement year. Therefore, the interval between measurement periods needs to be further narrowed, e.g., once every year, rather than every two years, to more closely reflect the rapid technological changes in exposure assessment. Another important aspect is to establish a common measurement protocol in the form of a multinational study, collect EMF exposure data for the mobile communication environment, and share the data for a health risk analysis, such as epidemiological studies.

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REFERENCES

[1] E. Cardis, "The interphone study: Design, epidemiological methods, and description of the study population," *Eur. J. Epidemiol.*, vol. 22, pp. 644–647, Oct. 2007. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/17636416
[2] S. Sadetzki, "The MOBI-kids study protocol: Challenges in assessing childhood and adolescent exposure to electromagnetic fields from wireless telecommunication technologies and possible association with brain tumor risk," *Frontiers Public Health*, vol. 2, Sep. 2014, Art. no. 124. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4172002/
[3] Y.-H. Byun, M. Ha, H.-J. Kwon, Y.-C. Hong, J.-H. Leem, J. Sakong, S. Y. Kim, C. G. Lee, D. Kang, H.-D. Choi, and N. Kim, "Mobile phone use, blood lead levels, and attention deficit hyperactivity symptoms in children: A longitudinal study," *PLoS ONE*, vol. 8, no. 3, Mar. 2013, Art. no. e59742. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3605379/
[4] S. Thomée, "Mobile phone use and mental Health. A review of the research that takes a psychological perspective on exposure," *Int. J. Environ. Res. Public Health*, vol. 15, no. 12, p. 2692, Nov. 2018. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6314044/
[5] A. Schoeni, K. Roser, and M. Röösli, "Symptoms and cognitive functions in adolescents in relation to mobile phone use during night," *PLoS ONE*, vol. 10, no. 7, Jul. 2015, Art. no. e0133528. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/26222312
[6] *IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques*, Standard 1528-2013, 2013. [Online]. Available: https://ieeexplore.ieee.org/document/6589093
[7] *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices—Part 1: Devices used next to the ear (Frequency range of 300 MHz to 6 GHz)*, Standard IEC62209-1, Jul. 2016. [Online]. Available: https://webstore.iec.ch/publication/25336

[8] *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, Standard C95.1, 1999. [Online]. Available: (https://ieeexplore.ieee.org/document/757105)
[9] *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, Standard C95.1, 2005. [Online]. Available: https://ieeexplore.ieee.org/document/1626482
[10] The International Commission on Non-Ionizing Radiation Protection, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)," *Health Phys.*, vol. 74, no. 4, pp. 494–522, Apr. 1998. [Online]. Available: https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf
[11] D. J. Gibson, *The Mobile Communications Handbook*, 2nd ed. Boca Raton, FL, USA: CRC Press, 1999. [Online]. Available: http://pws.npru.ac.th/sartthong/data/files/IEEE.Press_The.Mobile.Communications.Handbook_Pages7007.pdf
[12] A. Gati, A. Hadjem, M.-F. Wong, and J. Wiart, "Exposure induced by WCDMA mobiles phones in operating networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 12, pp. 5723–5727, Dec. 2009. [Online]. Available: https://ieeexplore.ieee.org/document/5351684
[13] M. Vrijheid, "Determinants of mobile phone output power in a multinational study: Implications for exposure assessment," *Occupational Environ. Med.*, vol. 66, no. 10, pp. 664–671, Oct. 2009. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/19465409, doi: 10.1136/oem.2008.043380.
[14] T. Persson, C. Törnevik, L.-E. Larsson, and J. Lovén, "Output power distributions of terminals in a 3G mobile communication network," *Bioelectromagnetics*, vol. 33, no. 4, pp. 320–325, May 2012. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/bem.20710
[15] P. Joshi, D. Colombi, B. Thors, L.-E. Larsson, and C. Tornevik, "Output power levels of 4G user equipment and implications on realistic RF EMF exposure assessments," *IEEE Access*, vol. 5, pp. 4545–4550, 2017. [Online]. Available: https://ieeexplore.ieee.org/document/7879218
[16] M. Han, A.-K. Lee, H.-D. Choi, Y. W. Jung, and J. S. Park, "Averaged head phantoms from magnetic resonance images of korean children and young adults," *Phys. Med. Biol.*, vol. 63, no. 3, Jan. 2018, Art. no. 035003. [Online]. Available: https://iopscience.iop.org/article/10.1088/1361-6560/aaa1c7/meta
[17] A.-K. Lee, J. S. Park, S.-E. Hong, M. Taki, K. Wake, J. Wiart, and H.-D. Choi, "Brain SAR of average male Korean child to adult models for mobile phone exposure assessment," *Phys. Med. Biol.*, vol. 64, Dec. 2019, Art. no. 045004. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/30719982
[18] A.-K. Lee, Y. Yoon, S. Lee, B. Lee, S.-E. Hong, H.-D. Choi, and E. Cardis, "Numerical implementation of representative mobile phone models for epidemiological studies," *J. Electromagn. Eng. Sci.*, vol. 16, no. 2, pp. 87–99, Apr. 2016. [Online]. Available: http://jees.kr/upload/pdf/jees-16-2-87.pdf
[19] A.-K. Lee, S.-E. Hong, J.-H. Kwon, H.-D. Choi, and E. Cardis, "Mobile phone types and SAR characteristics of the human brain," *Phys. Med. Biol.*, vol. 62, no. 7, pp. 2741–2761, Apr. 2017. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/28267685

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